Physics / Optimizatization Overview

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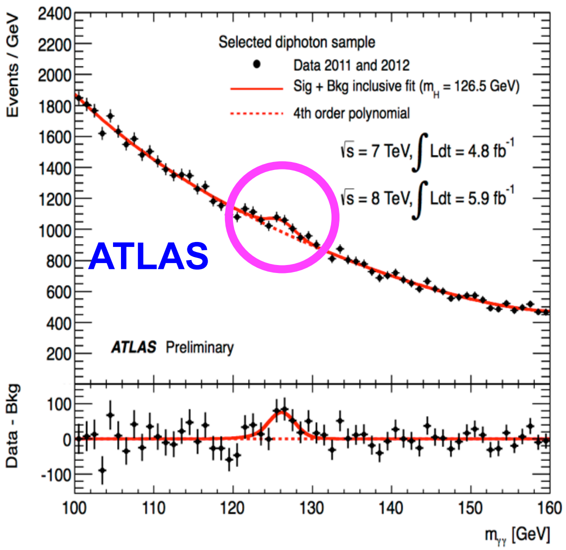
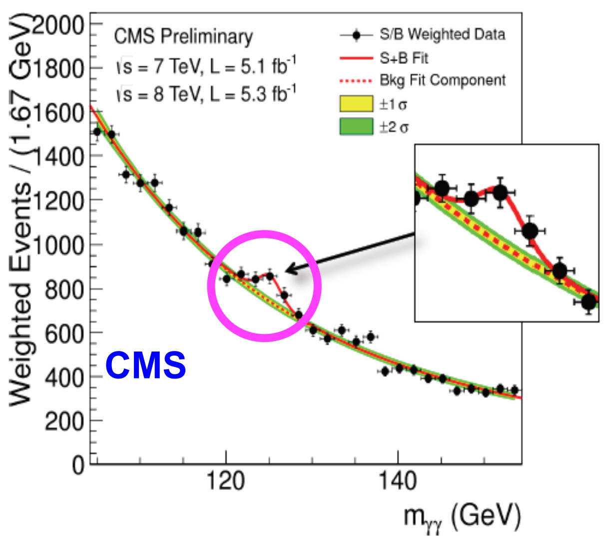
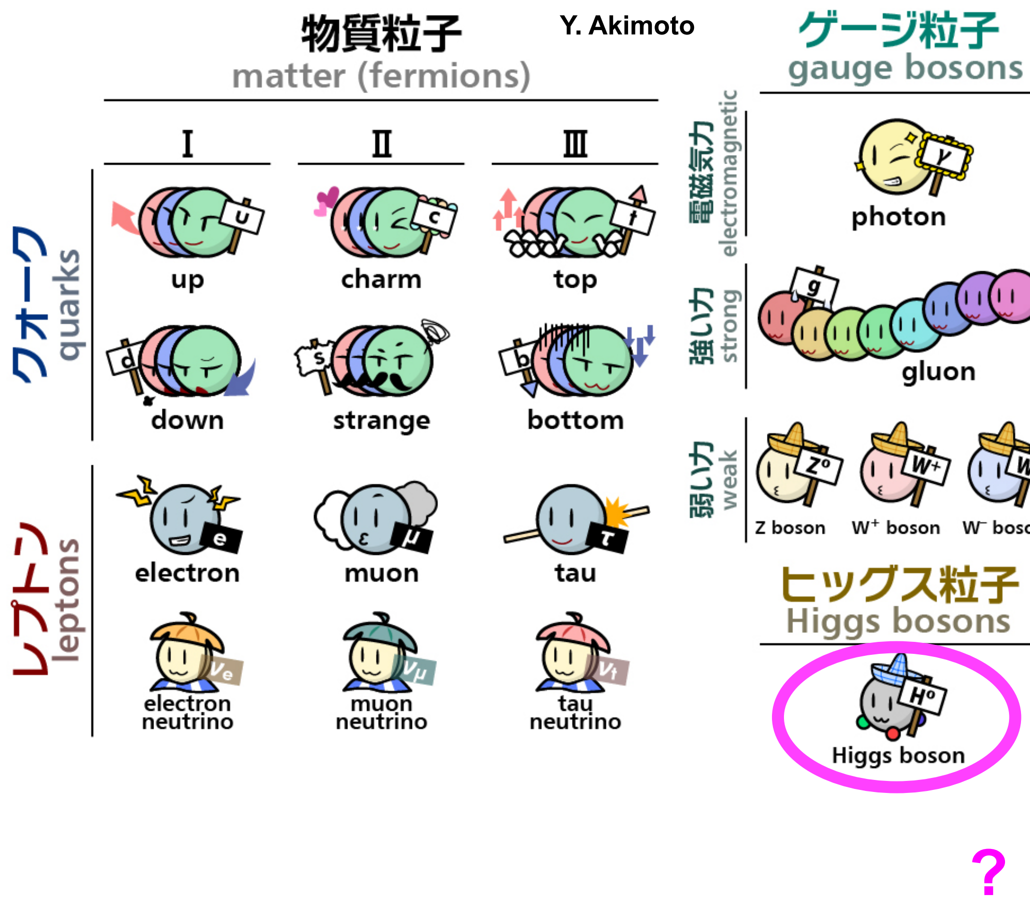
ICEPP, The University of Tokyo

JSPS Specially-Promoted Research, Annual Meeting
December 21, 2012

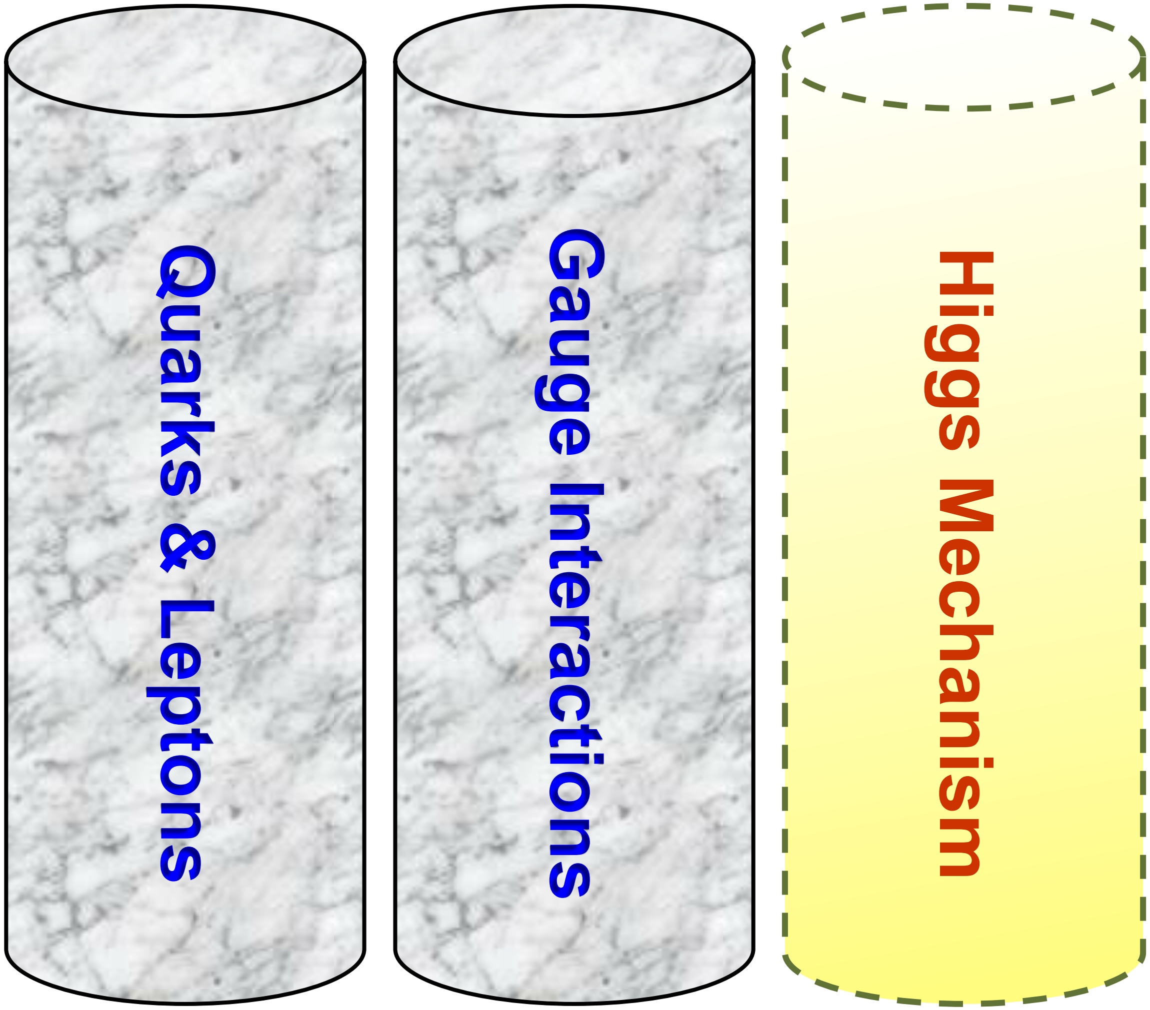
July 4, 2012 – Discovery of new boson





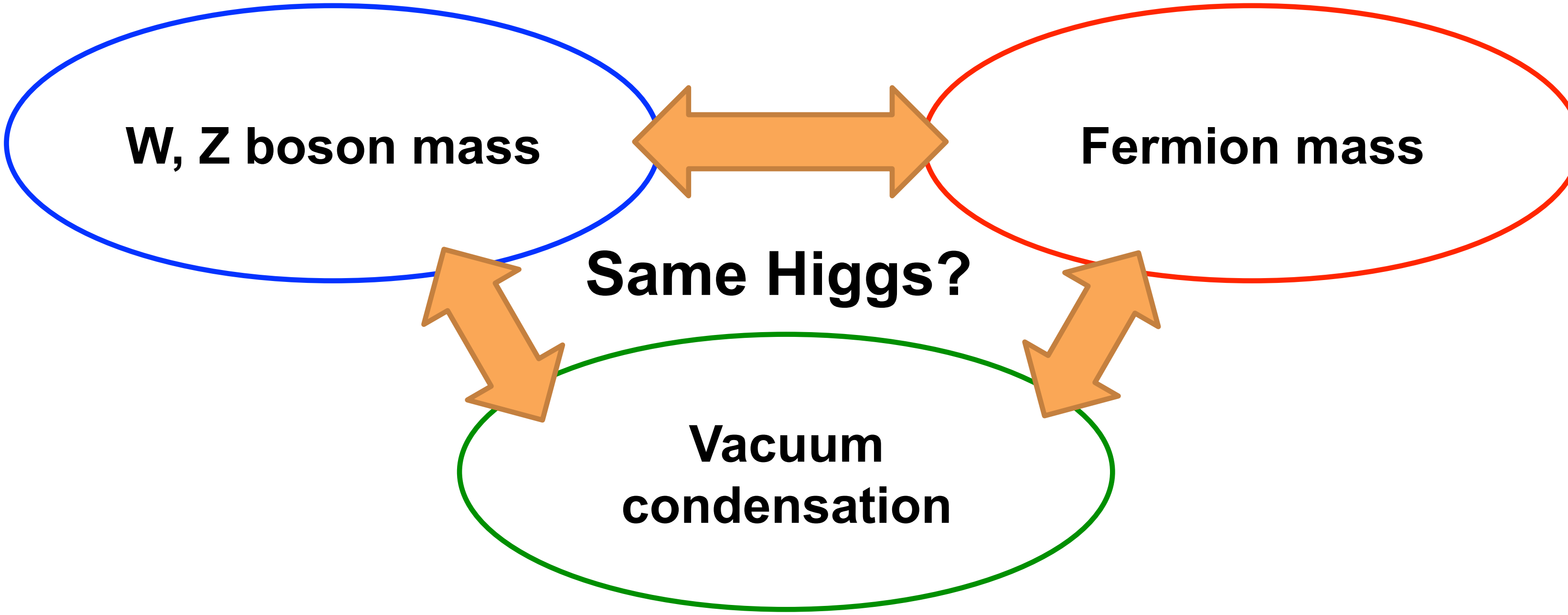


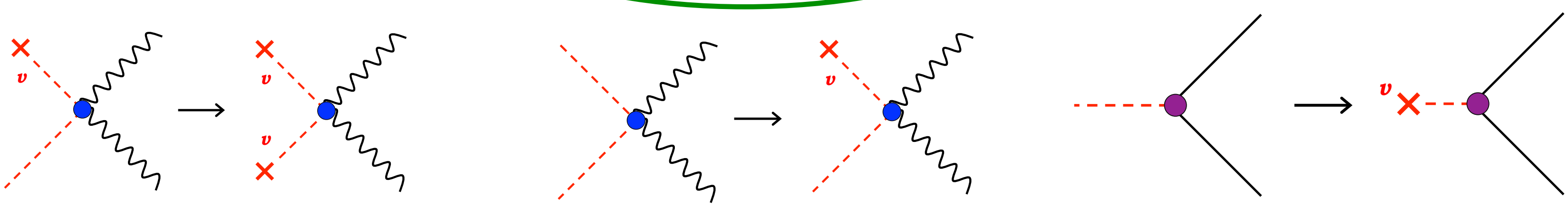
Pillars of Standard Model



The Higgs Boson

The Higgs boson plays a unique role in the SM:



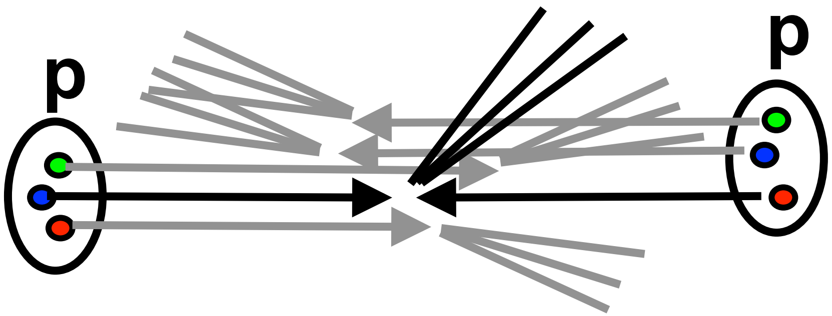


HWW, HZZ coupling | Higgs self-coupling | Yukawa coupling

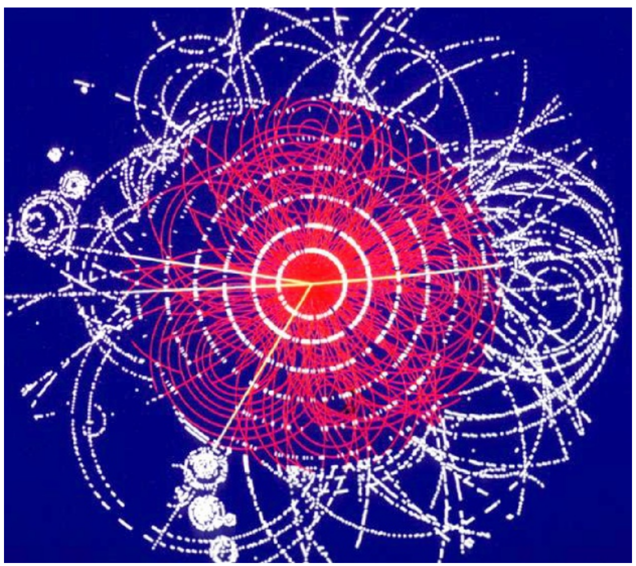
SM contains the simplest possible Higgs sector.
There is no known principle for this simplicity.

Energy Frontier Colliders

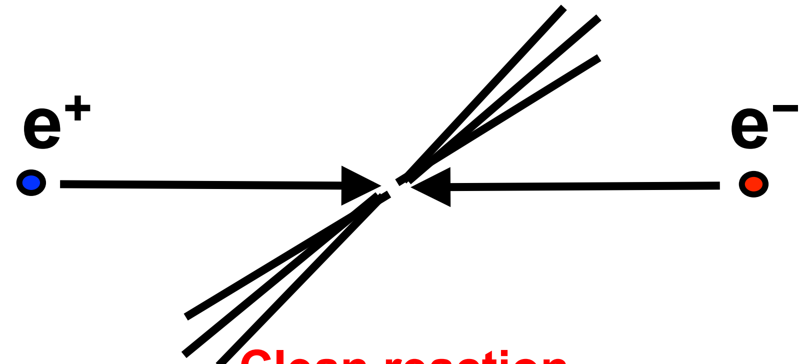
LHC: pp collider



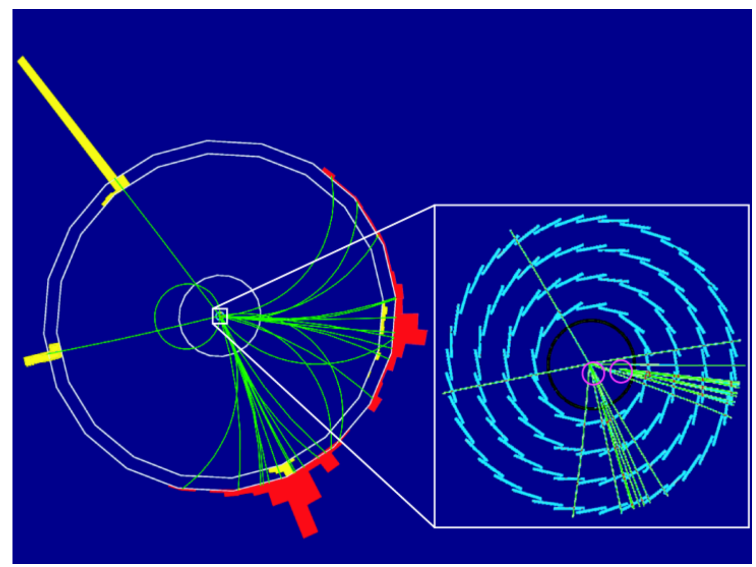
Multiple reactions
Initial energy unknown
Center-of-mass energy: 7-14 TeV



ILC: e^+e^- collider

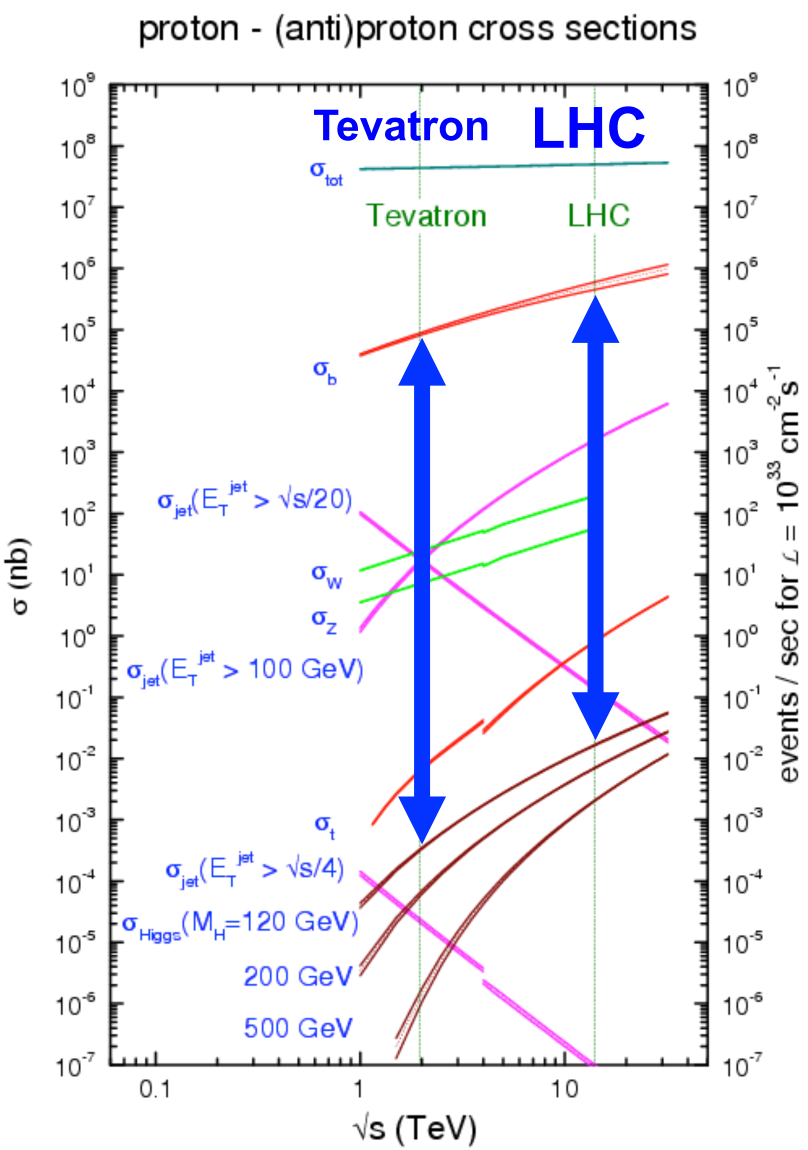


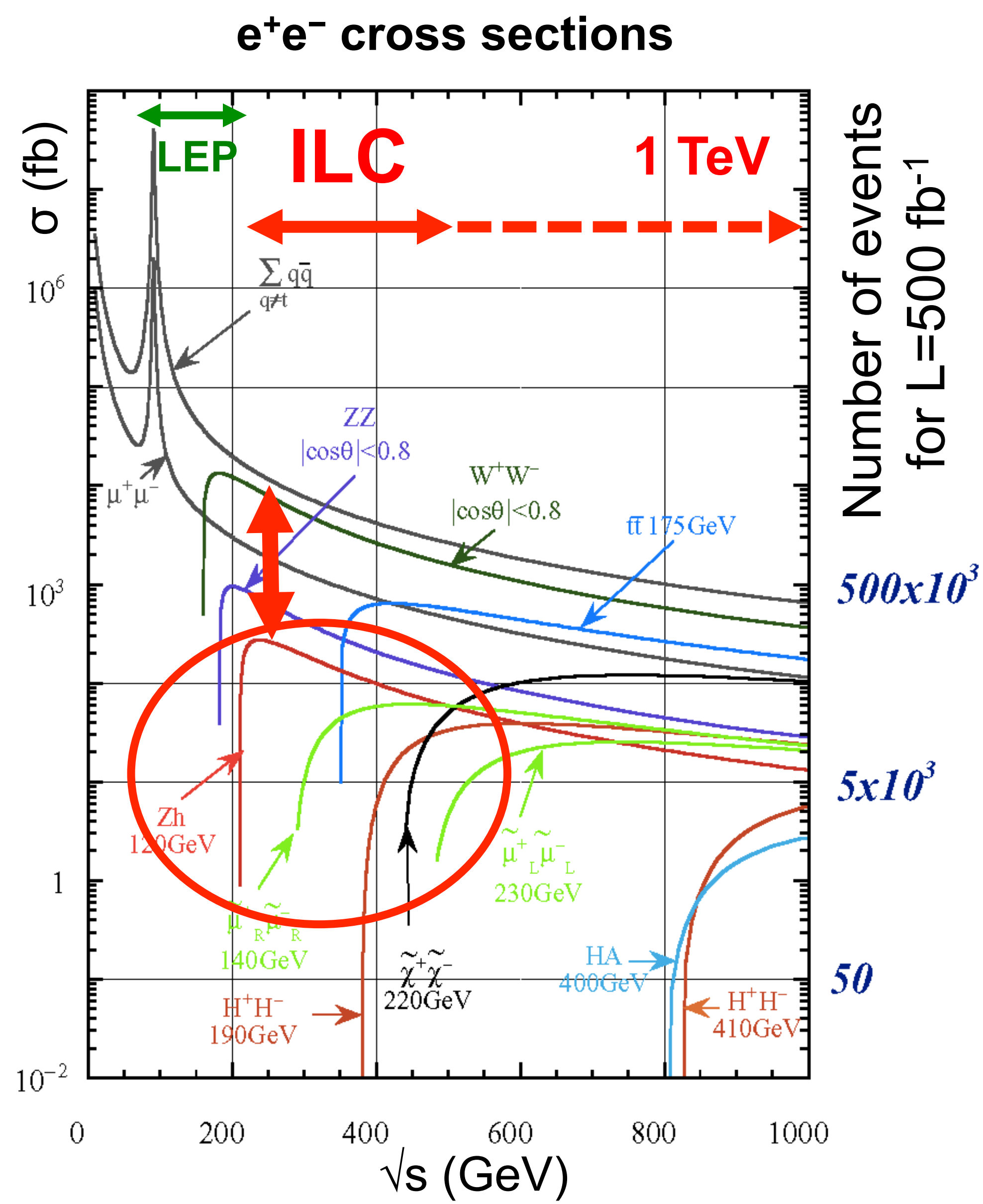
Clean reaction
Initial energy known
Center-of-mass energy: **250-1000 GeV**



Complementarity in new physics reach (parameter space)

Cross Sections



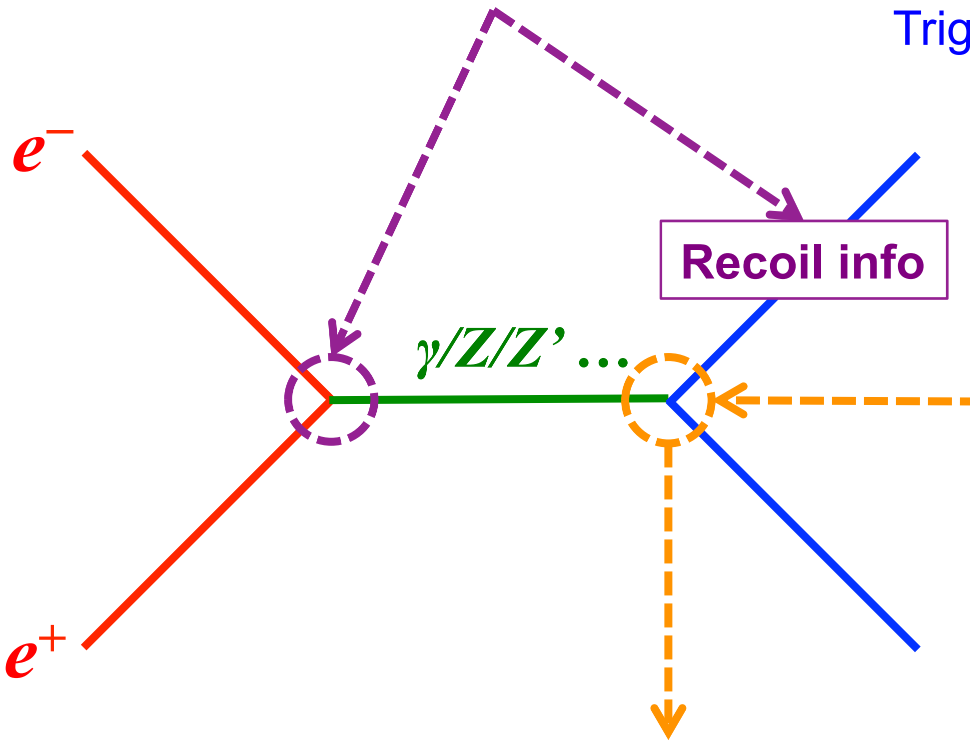


Characteristics of ILC

Beam
Tunable energy
Polarization
$P_{electron}$ = ±80%
$P_{positron}$ = ±30%

Elementary process
Well-understood at LEP
Theoretical uncertainty <1%

Detection
Low background
Highly granular sensors
Trigger free operation



Production
Higgs boson
Top quark
New particles, e.g.
Dark Matter
etc

Determine: Mass, J/CP, Couplings, etc
Discover: New Physics & New Principles

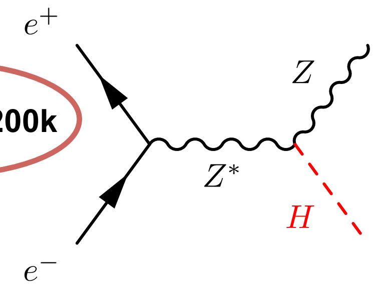
Physics Program at the ILC

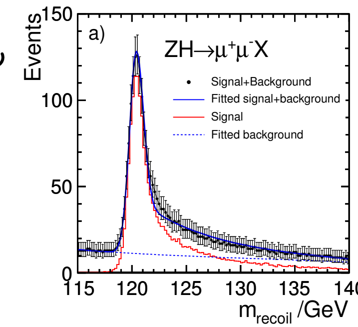
250~500 GeV

Higgs Factory

Observe vacuum condensation
Verify origin of mass
Multiple Higgs? (e.g. SUSY)
Discover new physics

 # Higgs > 200k



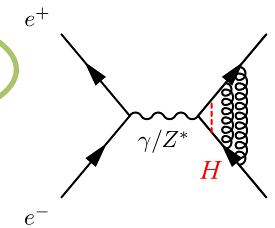


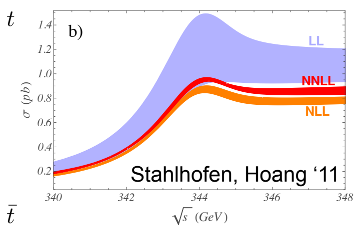
350 GeV

Top Factory

Why is the top quark so heavy?
Precision top mass measurements

 # top > 100k



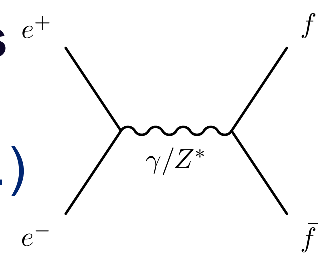


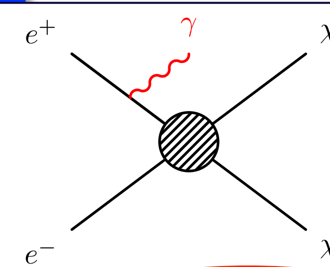
Electroweak Unification | **Mass Generation** | **Spontaneous Symmetry Breaking**

250~ GeV

"New Particle" Factory / Indirect Searches

Dark matter
Other color neutral states (heavy Higgs, *Z'* …)
Direct and indirect searches

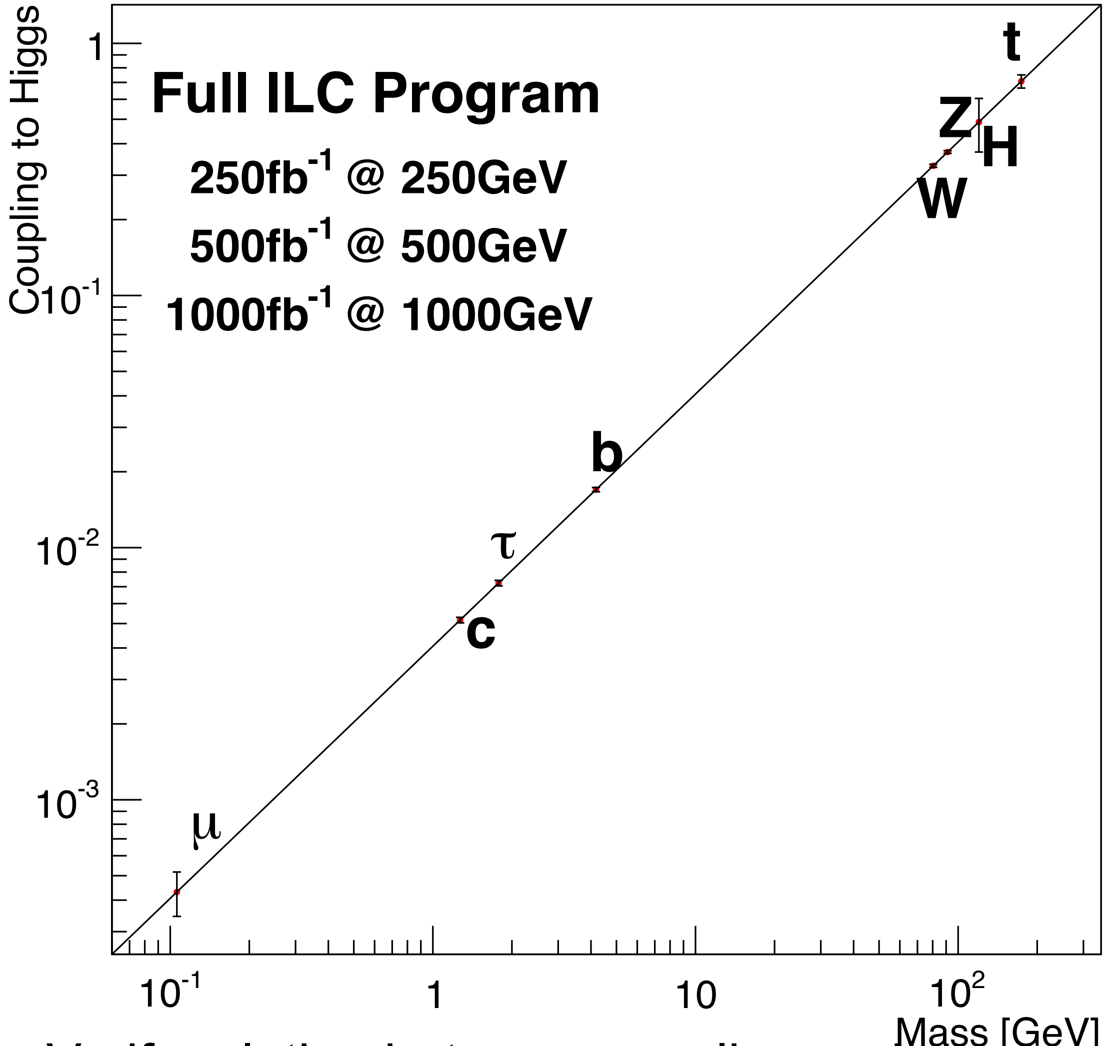




DM pair production?

Physics Beyond the Standard Model

Verification of Mass Generation



Verify relation between coupling and mass
→ confirmation of mass generation mechanism
Any deviation is a sign of new physics.

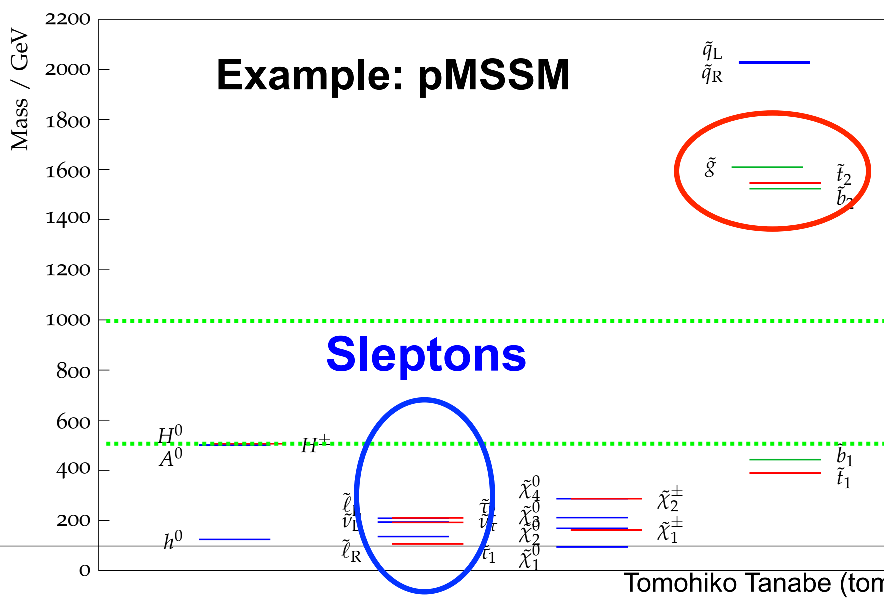
New Physics at the TeV scale

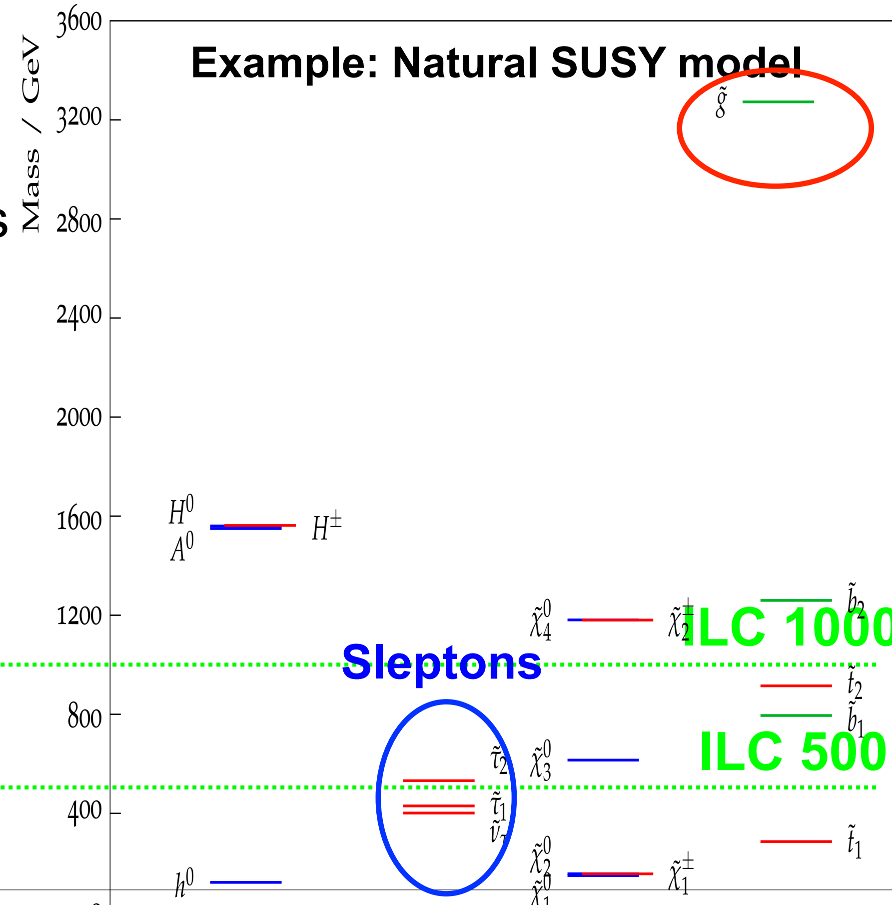
Two issues motivate the study of physics at **TeV scale**:

- **Naturalness**
  - Radiative correction to Higgs mass term has quadratic divergence
  - Require new physics / new particles in the TeV range to avoid excessive fine-tuning
    - e.g. Supersymmetry (SUSY), Composite Higgs, Extra Dimensions
- **Dark Matter (DM)**
  - WMAP relic density predicts O(100) GeV WIMP
  - New physics models predict natural DM candidates

Supersymmetry

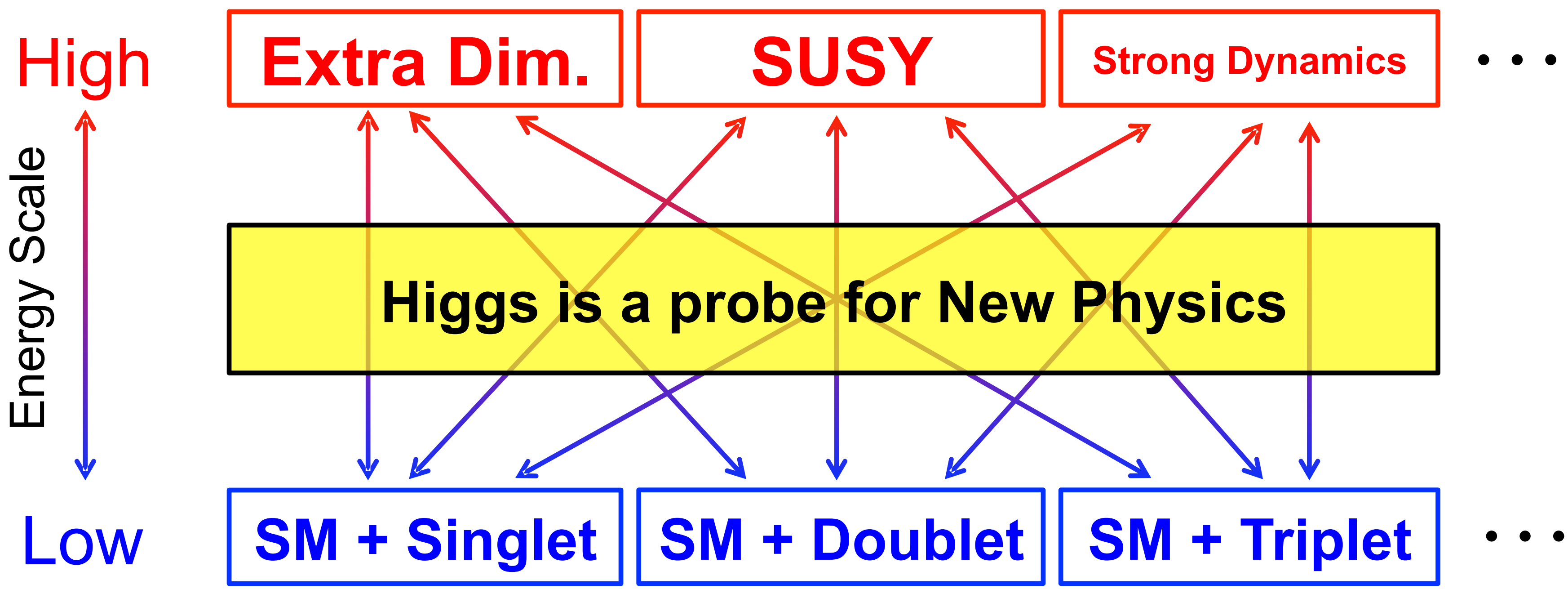
- **Colored SUSY** constrained by **LHC**
  - **m > 1.5 TeV** for **gluino**, **1st/2nd gen squarks**
  - Expect **> 2-3 TeV** at full energy
  - **Top squark** searches at **LHC**
- Light **colorless** particles (**sleptons, gauginos**) still alive (esp. small mass differences) → Probe at **ILC**





Higgs Sector and New Physics

New physics can affect the **Higgs sector**

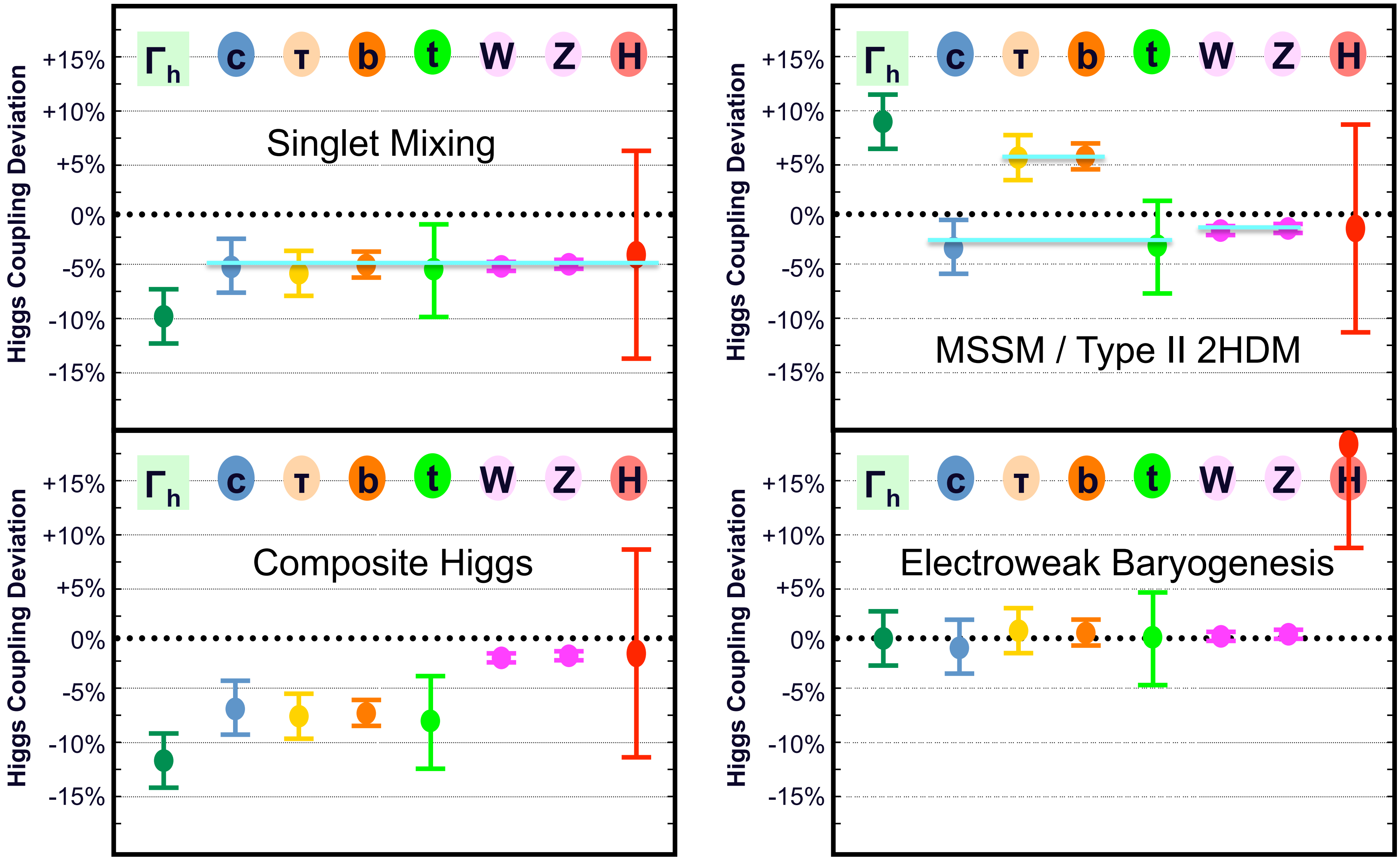


Extended Higgs Sector

May be able to explain well-established BSM phenomena: dark matter, neutrino oscillation, baryon asymmetry, etc.

Model "Finger-printing"

Higgs Coupling Precision with "Full ILC Program" x2~3 (Model-Independent Analysis)



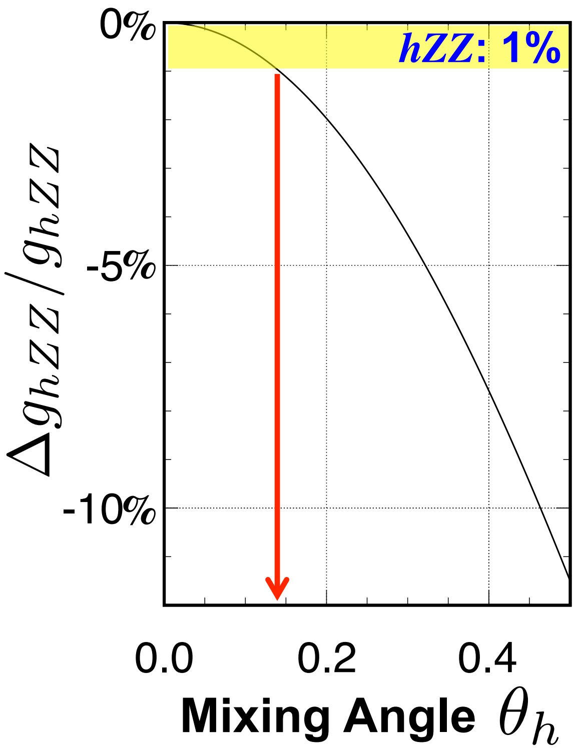
Identify new physics pattern via precision measurement of Higgs couplings

Sensitivity to New Physics

Higgs-Singlet Mixing

e.g. $U(1)_{B-L}$, Radion, Dilaton

$$\frac{\Delta g_{hVV}}{g_{h_{SM}VV}} \approx -\sin^2\theta_h/2$$

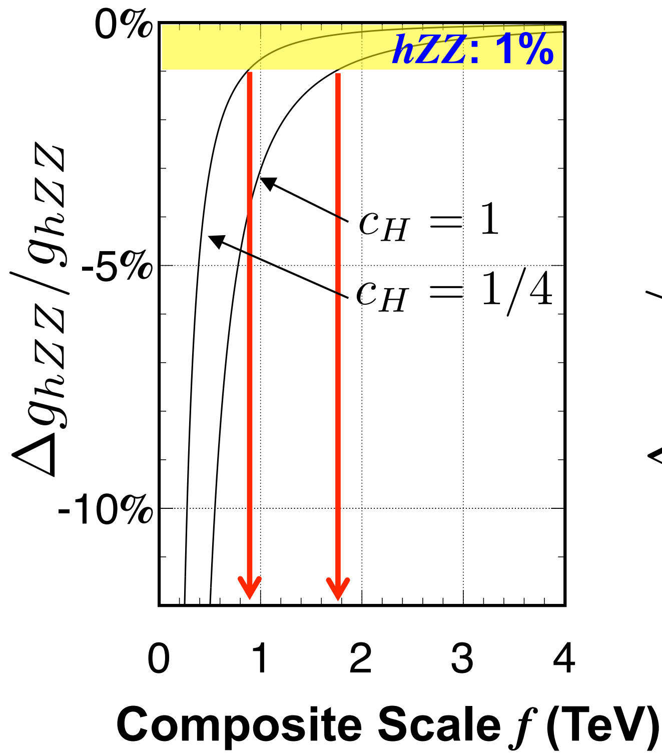


θ_h < 0.15 rad

Composite Higgs

e.g. Little Higgs, Holographic Higgs

$$\frac{\Delta g_{hVV}}{g_{h_{SM}VV}} \approx -c_H\xi/2, \quad \xi = v^2/f^2$$



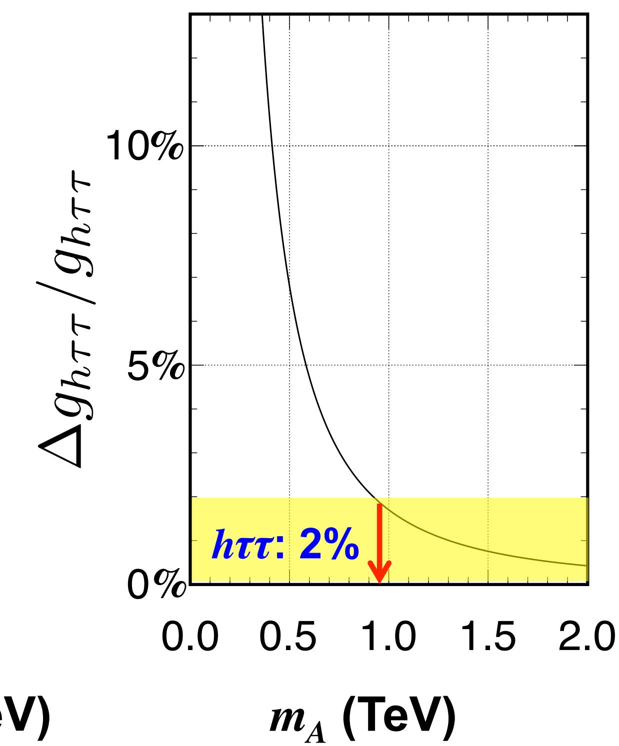
f > 1-2 TeV

(Sensitivity from Higgs sector alone)

MSSM

tan β = 5, radiative corr.~1

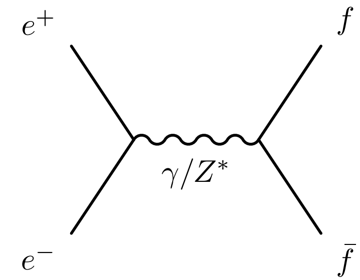
$$\frac{\Delta g_{hbb}}{g_{h_{SM}bb}} = \frac{\Delta g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1.7\% \left(\frac{1\text{TeV}}{m_A}\right)^2$$

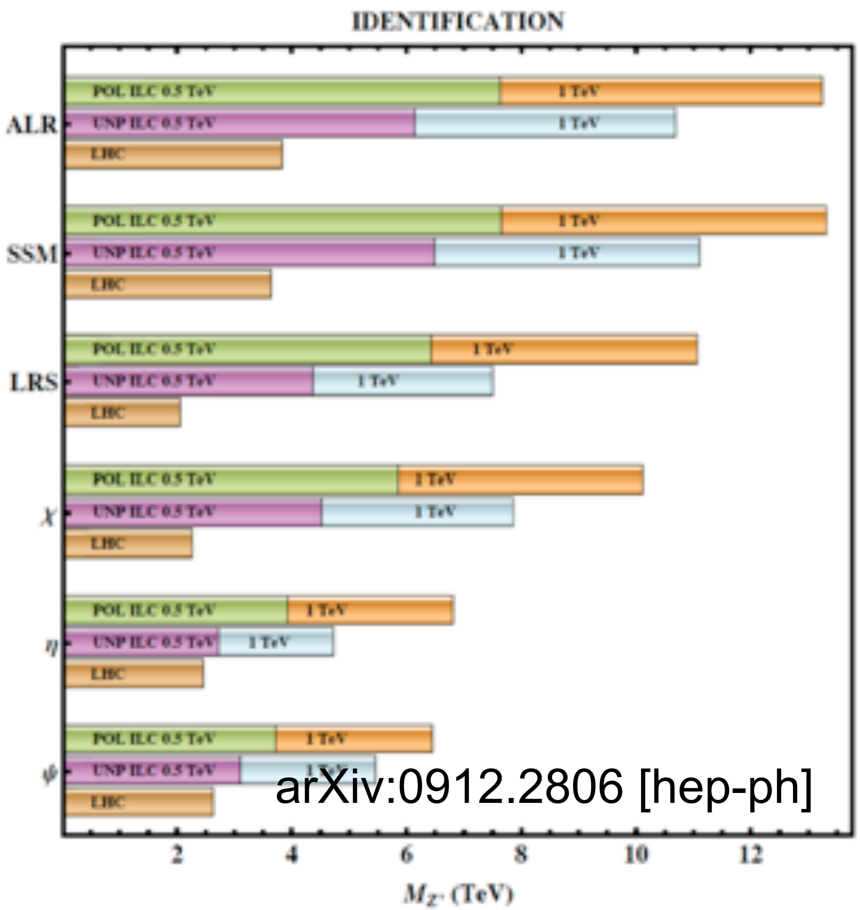


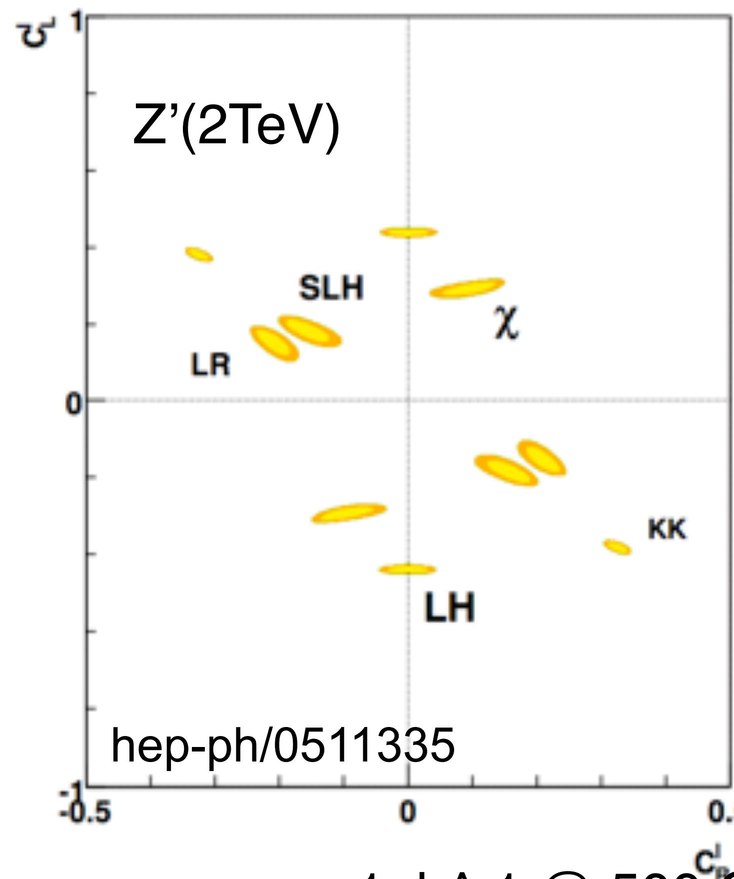
m_A > 1 TeV (tan β = 5)

Search for Z' boson

Polarized differential cross sections: LL/RR/LR/RL
Forward-backward asymmetries







1ab^-1 @ 500 GeV

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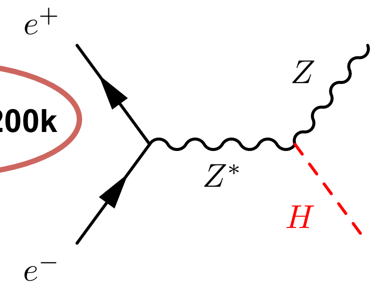

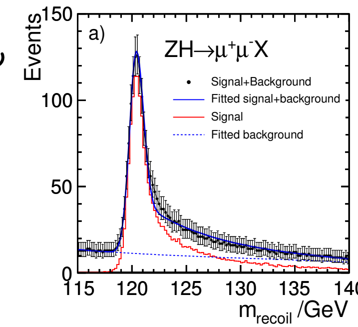

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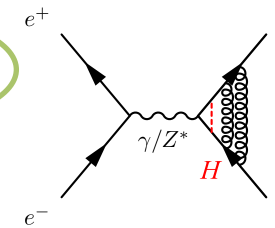

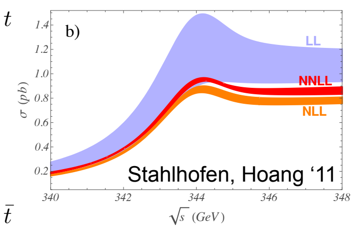

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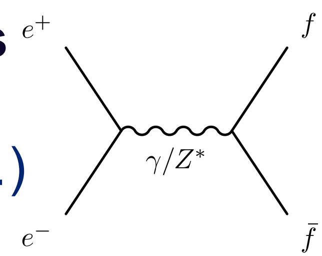
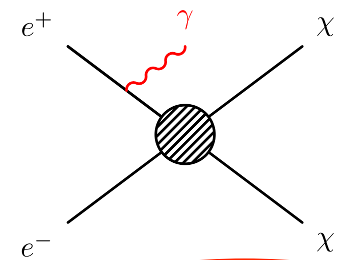




DM pair production?

Physics Beyond the Standard Model

Physics / Optimization

- Physics / Optimization activities driven by DBD in 2012
- Post-LOI analyses were performed → they go into the DBD Physics Chapter.
- DBD benchmark analyses were performed.
- Will summarize our Physics WG activities.
- Will highlight some results not yet presented this morning.

DBD Physics Chapter

Draft available at:
http://lcsim.org/papers/DBDPhysics.pdf
(220 pages, Dec. 13 version)

Editors:
Introduction (Jae Yu, Michael Peskin)
W and Z Boson Physics (Tim Barklow, Jürgen Reuter)
Two-Fermion Processes (Yuanning Gao, Maxim Perelstein)
Top Quark (Roman Poeschl, Andrei Nomerotski, Andre Hoang)
Standard Model Higgs (Keisuke Fujii, Heather Logan)
Extended Higgs (Aurore Savoy-Navarro, Shinya Kanemura)
Supersymmetry (Jenny List, Howard Baer)
Cosmological Connection (Geraldine Servant, Tim Tait)

Numerous contributions from our working group!

DBD Benchmarks

Analyses at √s=1 TeV:

1) **vvh** w/ h→bb,cc,gg,WW*,μμ **[H. Ono, C. Calancha]**

2) **WW** for polarization [A. Rosca]

3) **tth** [T. Price, **TT**]

Analyses at √s=500 GeV:

4) **Top pair** [J. Rouene, S. Amjad]

5) **Higgs self-coupling** [**J. Tian**]

Analysts have worked hard to deliver results for the DBD draft. ILD internal review process will begin soon. Finalized results to be aimed for mid-January.

Physics WG

- Asian ILC Physics Working Group
  - Mailing list: ilcphys@ml.post.kek.jp
  - Contact me / Fujii-san to join
- We hold remote meetings (almost) every Friday at 13:30 via KEK MCU system
  - Discussion on physics analyses and reconstruction software.
  - Agenda: http://ilcagenda.linearcollider.org/categoryDisplay.py?categId=131
- Face-to-face meeting every ~two months at KEK: **General Meeting of Physics WG**. The focus is on ILC physics. We have very active participation of theorists. Last meeting was held on October 13 (sat) – next meeting is scheduled to be Saturday, January 12, 2013.
  - Meeting website: http://ilcphys.kek.jp/meeting/physics/

Physics WG: EWSB

Higgs branching ratios

- **ZH, H→bb,cc,gg (250 + 350 GeV):** paper submitted to EPJ **[H. Ono, A. Miyamoto]**
- **ZH, H→WW* anomalous coupling (250 GeV):** paper submitted to PRD **[Y. Takubo]**
- **ZH, H→γγ (250 GeV):** in progress **[C. Calancha]**
- **ZH, H→ττ (250 GeV):** Z→qq,ll done, Z→νν next **[S. Kawada, T. Suehara, TT]**
- **ννH, H→WW*,ZZ* (500 GeV):** done for DBD **[J. Tian]**
- **ννH (1 TeV):** done for DBD **H→bb,cc,gg,WW*** **[H. Ono]** **H→μμ** **[C. Calancha]**

Higgs self-coupling

- **ZHH (500 GeV):** H→bb and Z→all: paper draft **[J. Tian, Y. Takubo]**
  - Reanalysis with improved analysis tools **[J. Tian, T. Suehara, TT]**
  - H→WW* mode: started **[M. Kurata]**
- **ννHH (1 TeV):** fast sim done, full sim ongoing **[J. Tian]**
- **γγ→HH (~300 GeV):** fast sim, **PRD 85 113009 (2012)** **[S. Kawada]**

Top Yukawa coupling

- **ttH (500 GeV + 1 TeV):** full sim done **[R. Yonamine, TT]**

Top pair at threshold

- **tt (350 GeV):** analysis started **[T. Horiguchi, A. Ishikawa]**

Physics WG: BSM

- **SUSY “point 5”:** full simulation → LOI, DBD
- **Z’ tail from e.g. extra U(1):** top pair, tau pair: full sim for LOI
- **Hidden Sector / Extra Dim:** PRD 78, 015008 (2008)
- **LHT:** $A_H Z_H$, $W_H W_H$ PRD 79, 075013 (2009), $+Z_H Z_H$, $e_H e_H$, $v_H v_H$ **[E. Kato]**
- **Model discrimination:** PRD 84, 115003 (2011) **[T. Saito, T. Suehara]**
- **Seesaw neutrino:** PRD 82, 093004 (2010) **[T. Saito]**
- **Very light gravitino:** master’s thesis, LCnote draft **[R. Katayama, T. Suehara, TT]**
- **Quasi stable stau:** master’s thesis, paper draft **[W. Yamaura, K. Kotera]**
- **Higgs portal:** **[T. Honda, A. Yamamoto]**
- **Theoretical contributions**
  - 6-dim derivative interactions PNG NHDMs: **Y. Kikuta**
  - Measurement of tanβ: **K. Tsumura**
  - Radiative seesaw: **H. Sugiyama, T. Nabeshima**
  - SUSY Higgs with EW baryogenesis: **T. Shindou**
  - SUSY-GUT + Hosotani: **T. Yamashita**
  - SUSY strong dynamics: **T. Yamada**

Highlights

- 1. Higgs portal scenario
- 2. Top pair at threshold
- 3. Top Yukawa coupling

Higgs Portal Scenario (1)

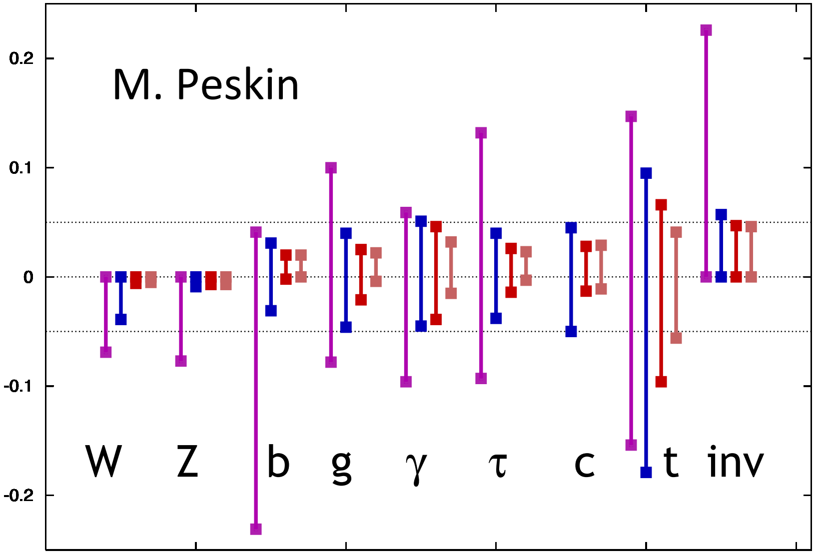
- Cold dark matter (DM) couples only to Higgs boson: an interesting possibility!
- Introduce discrete (Z_2) symmetry: makes DM stable.
- Viable models exist for scalar, fermionic, and vector DM.

$$\mathcal{L}_{\rm scalar} = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \boxed{\frac{\lambda_{HS}}{2} H^\dagger H S^2} - \frac{\lambda_S}{4} S^4$$

$$\mathcal{L}_{\rm fermion} = \overline{\psi}\left[i\gamma\cdot\partial - m_\psi\right]\psi - \boxed{\frac{\lambda_{H\psi}}{\Lambda} H^\dagger H\ \overline{\psi}\psi}$$

$$\mathcal{L}_{\rm vector} = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_\mu V^\mu + \frac{1}{4}\lambda_V (V_\mu V^\mu)^2 + \boxed{\frac{1}{4}\lambda_{HV} H^\dagger H V_\mu V^\mu}$$

$g(hAA)/g(hAA)|_{SM}-1$ LHC/ILC1/ILC/ILCTeV



Phenomenology of Higgs portal scenarios manifest in:

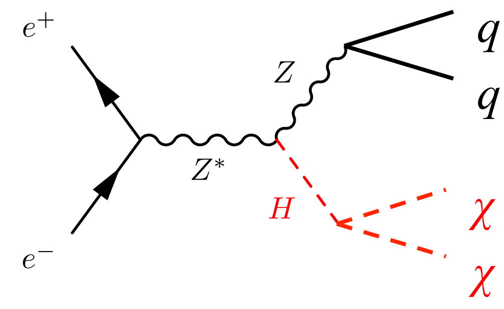
- Invisible decay of Higgs in collider
- Direct detection e.g. XENON100

But large parameter spaces still remain unexplored by experiment!

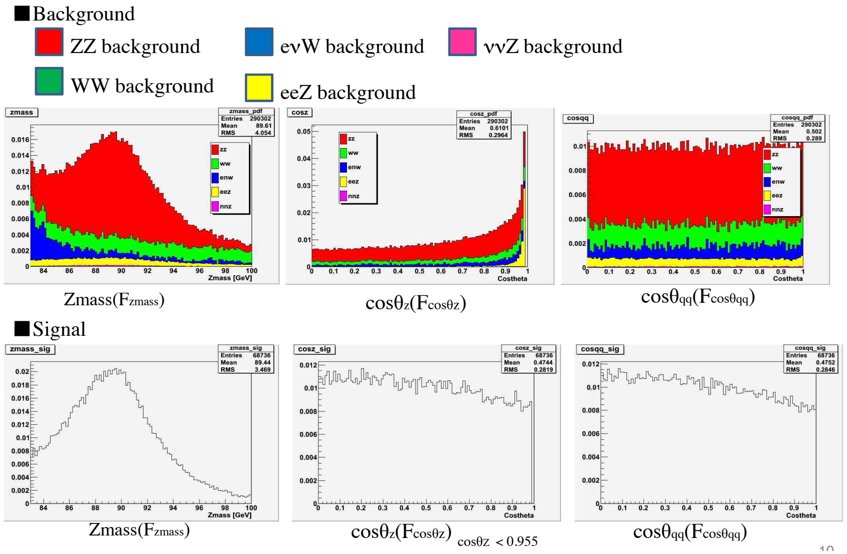
Higgs Portal Scenario (2)

A. Yamamoto

- Analysis in progress by T. Honda → **A. Yamamoto** @ Tohoku University
- Aim is to investigate the capabilities of ILC to probe the Higgs portal scenario
- Signal process: $e^+e^- \to Z(\to qq)\, H(\to \chi\chi)$, i.e. 2 jets + missing
- Model assumptions:
  - mH = 125 GeV
  - Fermionic DM with mass m_χ = 50 GeV
  - $\lambda_{H\psi}$ = 6.86 / 2 = 3.43, Λ = 1 TeV
  - Signal cross section: 15 fb
- Machine conditions: √s = 250 GeV
  Integrated luminosity = 1 ab^{-1}
  Beam polarizations: $(P_{e-}, P_{e+}) = (+0.8, -0.3)$

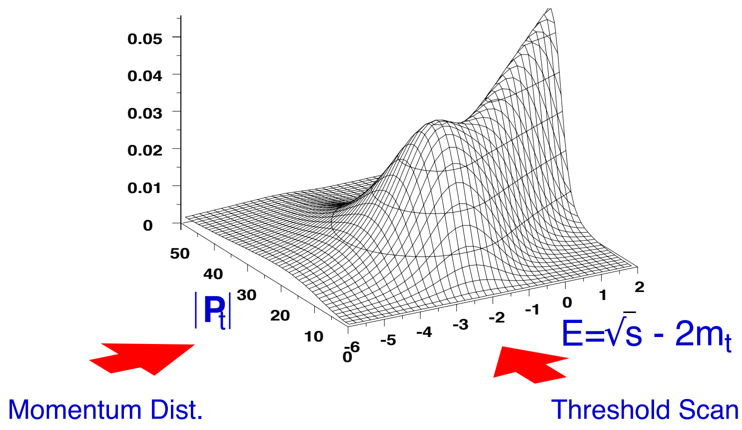


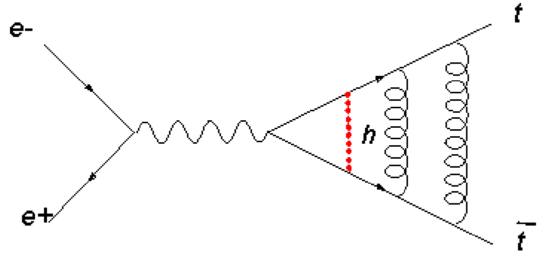
- Backgrounds: WW, ZZ, νν Z → ννqq, eνW → eνqq, eeZ → eeqq, ZH → ZZZ* → qq4ν
- Event selection based on: no isolated leptons, forward electron veto, Z candidate mass + angle
- With optimal cuts, upper limit is found to be **BR(H→χχ) < 0.3% (95% C.L.)**
- Next steps: vary DM mass

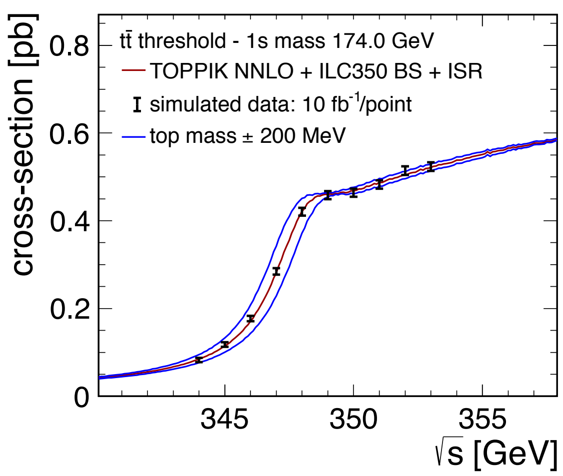


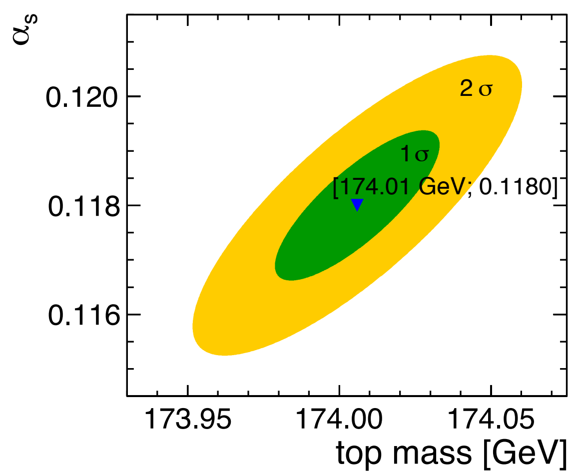
Top Pair Threshold

- Understanding of top quark is of paramount importance in understanding EWSB
- ILC will offer for the first time the measurement of the top pair threshold
- MSbar scheme mass measurements provide valuable input to theory
- Indirect top Yukawa measurement may be possible → full simulation study ongoing by **T. Horiguchi** (Tohoku)







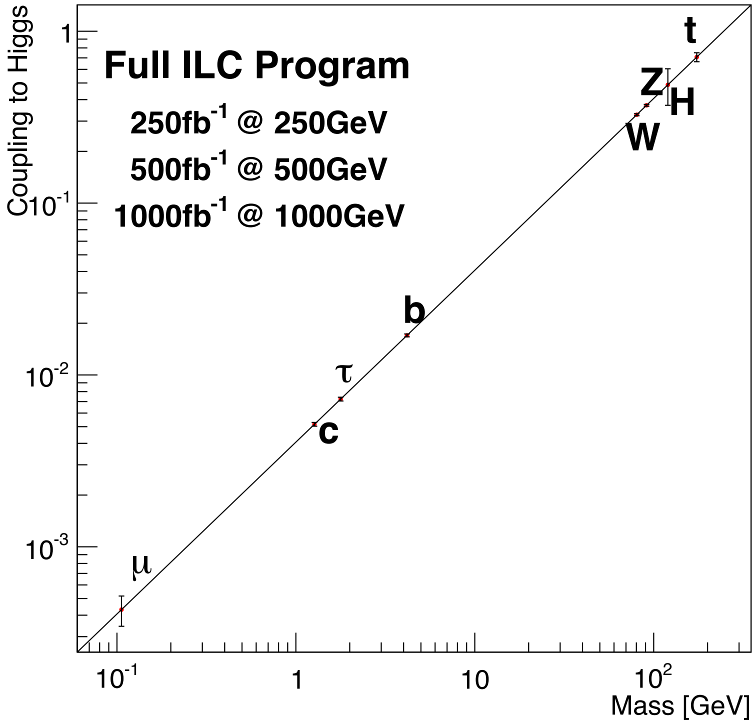


Expected statistical precision
$10\ fb^{-1}$ x 10 points

Observable	Precision
m_t	20 MeV
α_s	0.0012
Γ_t	32 MeV

Top Yukawa Coupling

- Top quark couples strongly to the Higgs boson (top Yukawa y_t~1)
- Important probe for verification of electroweak symmetry breaking
- Many BSM models predict **large deviations in y_t** e.g. composite Higgs models

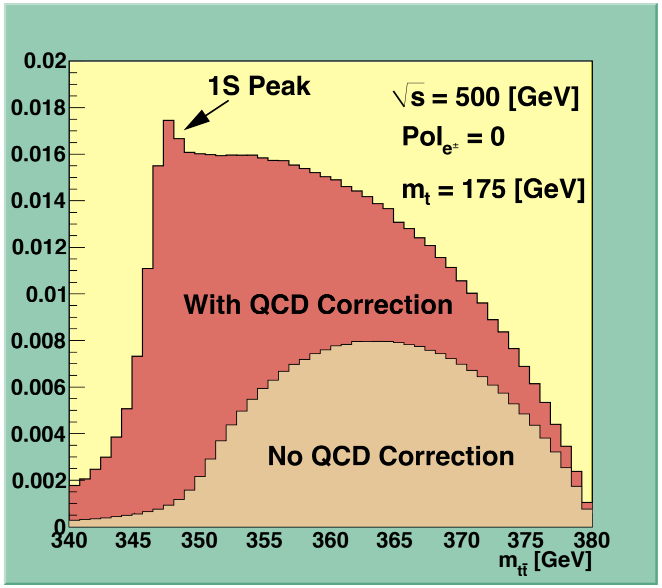


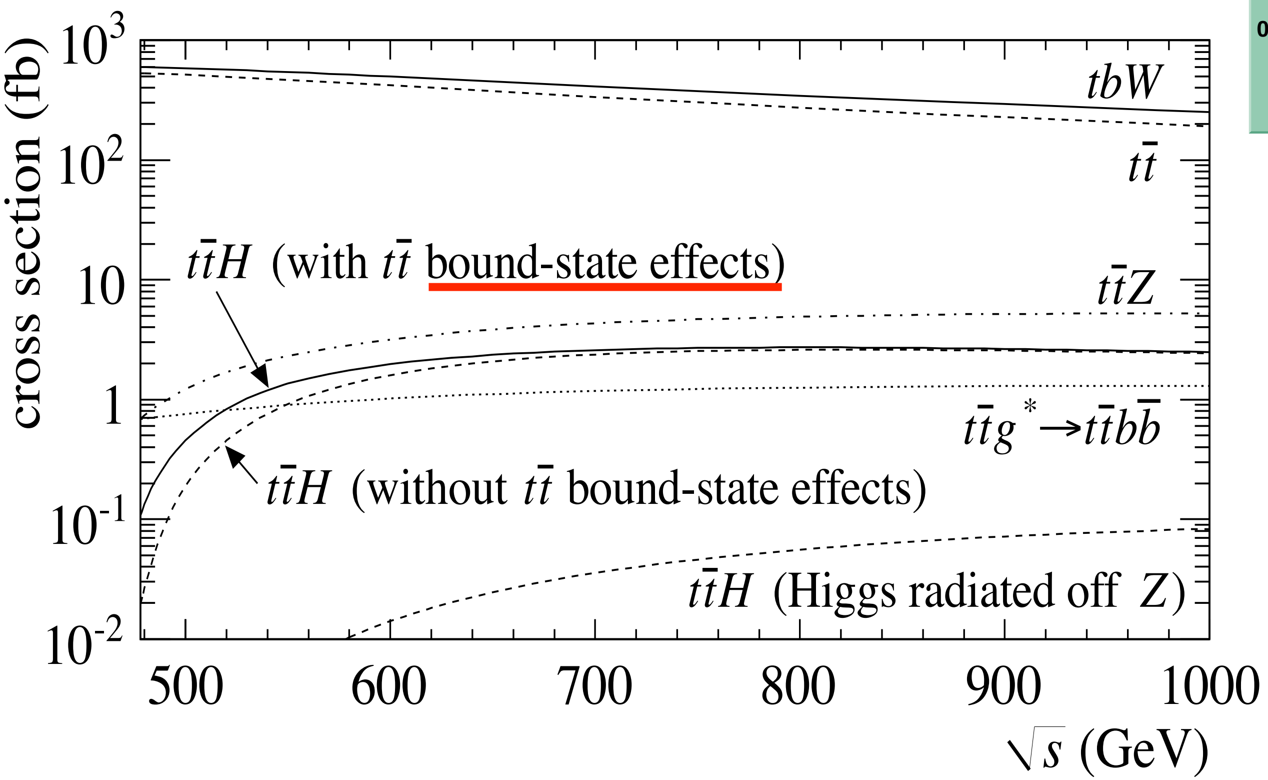
500 GeV full simulation (LOI samples): Ryo Yonamine (Ph.D. thesis)

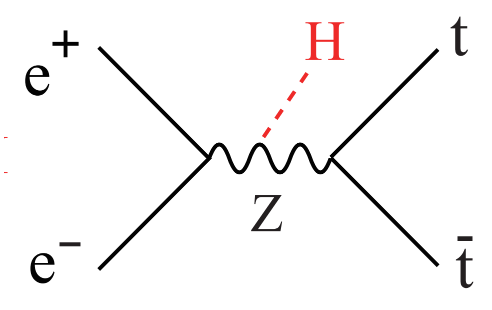
1 TeV full simulation (DBD samples): Tony Price, TT

Signal and Background

- **Signal: tth → bWbWbb**
- Irreducible backgrounds:
  - **ttZ** → bWbWbb
  - **ttg*** → bWbWbb
- Reducible background: **tt** → bWbW

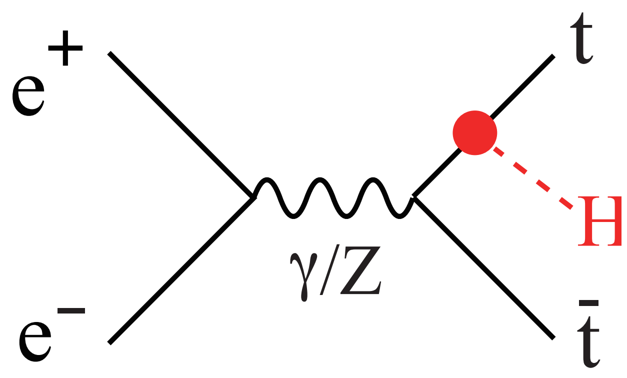






Signal mode

- Goal is to evaluate the precision of the top Yukawa coupling measurement at ILC at $\sqrt{s}$ = 500 GeV and 1 TeV
- **Higgs boson mass 125 GeV in light of LHC data.**
  - BR(H→bb) = 57.8%
- There are three decay modes depending on the W decay:
  - ttH → 4 jet + 2 lepton mode: BR(tt → blνblν) = 11% -- not analyzed
  - **ttH → 6 jet + lepton mode:** BR(tt → bqqblν) = 45% for l=e,μ,τ (29% for l=e,μ)
  - **ttH → 8 jet mode:** BR(tt → bqqbqq) = 44%

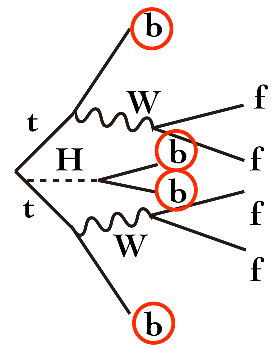


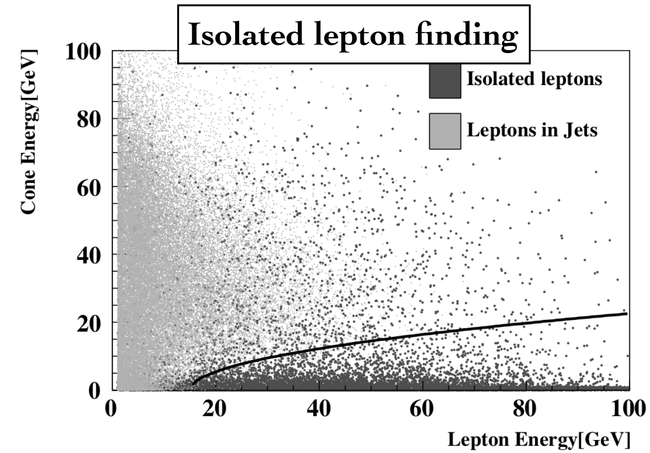
R. Yonamine -- 500 GeV

Strategy to Reduce Background

❖ **Mode selection**

# of Isolated leptons to be { **1: 1-lepton + 6-jet analysis** / **0: 8-jet analysis** }





❖ **Event shape cuts**

Thrust cut

$$T = \max_{|\hat{n}|=1} \frac{\sum_i |\hat{n}\cdot\vec{p}_i|}{\sum_i |\vec{p}_i|}$$

T~1-->2jet-like event

T~0-->multi jet-like event

Y cut

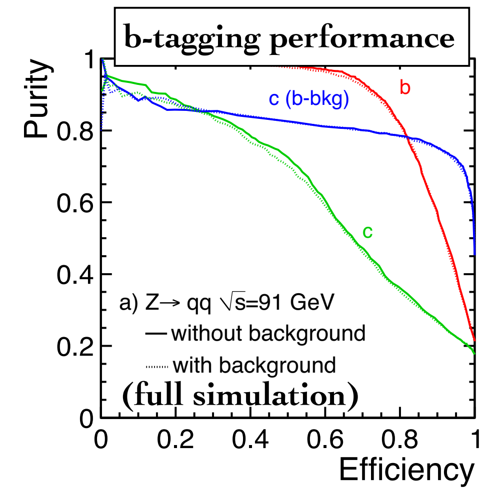
$$Y_{ij} = \frac{\min(E_i^2, E_j^2)(1-\cos\theta_{ij})}{E_{CM}^2}$$

Y depends on # of jets

(Durham Jet Clustering)

❖ **b-tagging**

finding b-jets by impact parameter significance.



❖ **mass reconstruction and mass cut**

We chose jet combination which minimize the following χ^2.

$$\chi^2 = \left(\frac{m_{j_1j_2}-M_H}{\sigma_H}\right)^2 + \left(\frac{m_{j_3j_4j_5}-M_t}{\sigma_t}\right)^2 + \left(\frac{m_{j_6j_7j_8}-M_t}{\sigma_t}\right)^2 + \left(\frac{m_{j_3j_4}-M_W}{\sigma_W}\right)^2 + \left(\frac{m_{j_6j_7}-M_W}{\sigma_W}\right)^2$$

H top top W W

(8-jet mode)

We chose cut values so that the signal significance becomes maximum.

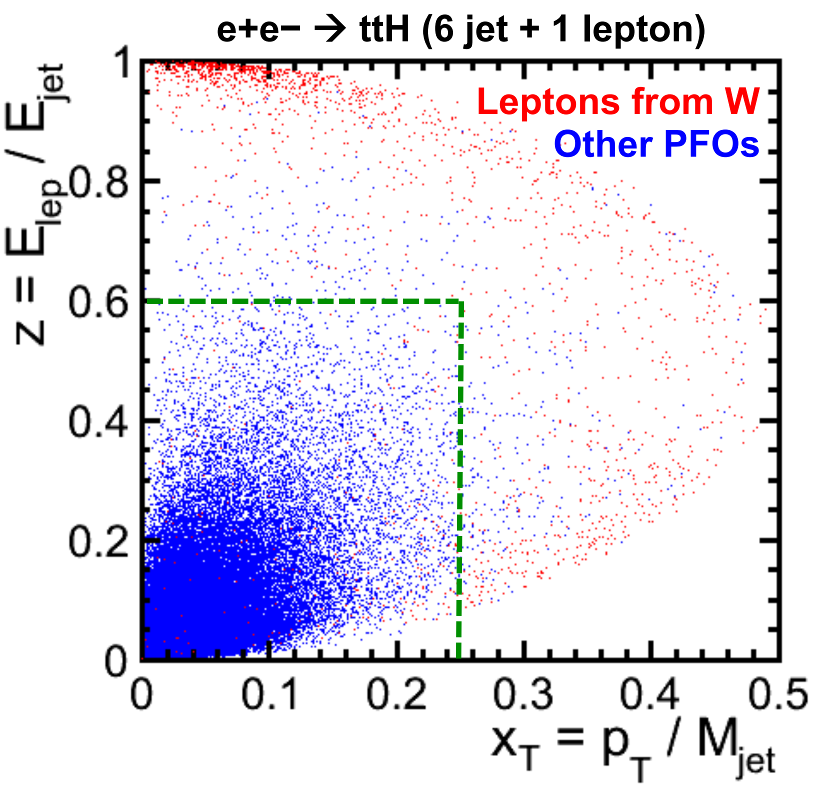
$$\sigma = \frac{S}{\sqrt{S+B}}$$

S: # of signal events

B: # of background events

Isolated Lepton Finding

1 TeV



Hard isolated leptons coming from W decay

- Useful discriminant for separating 6 jet + lepton mode / 8 jet mode

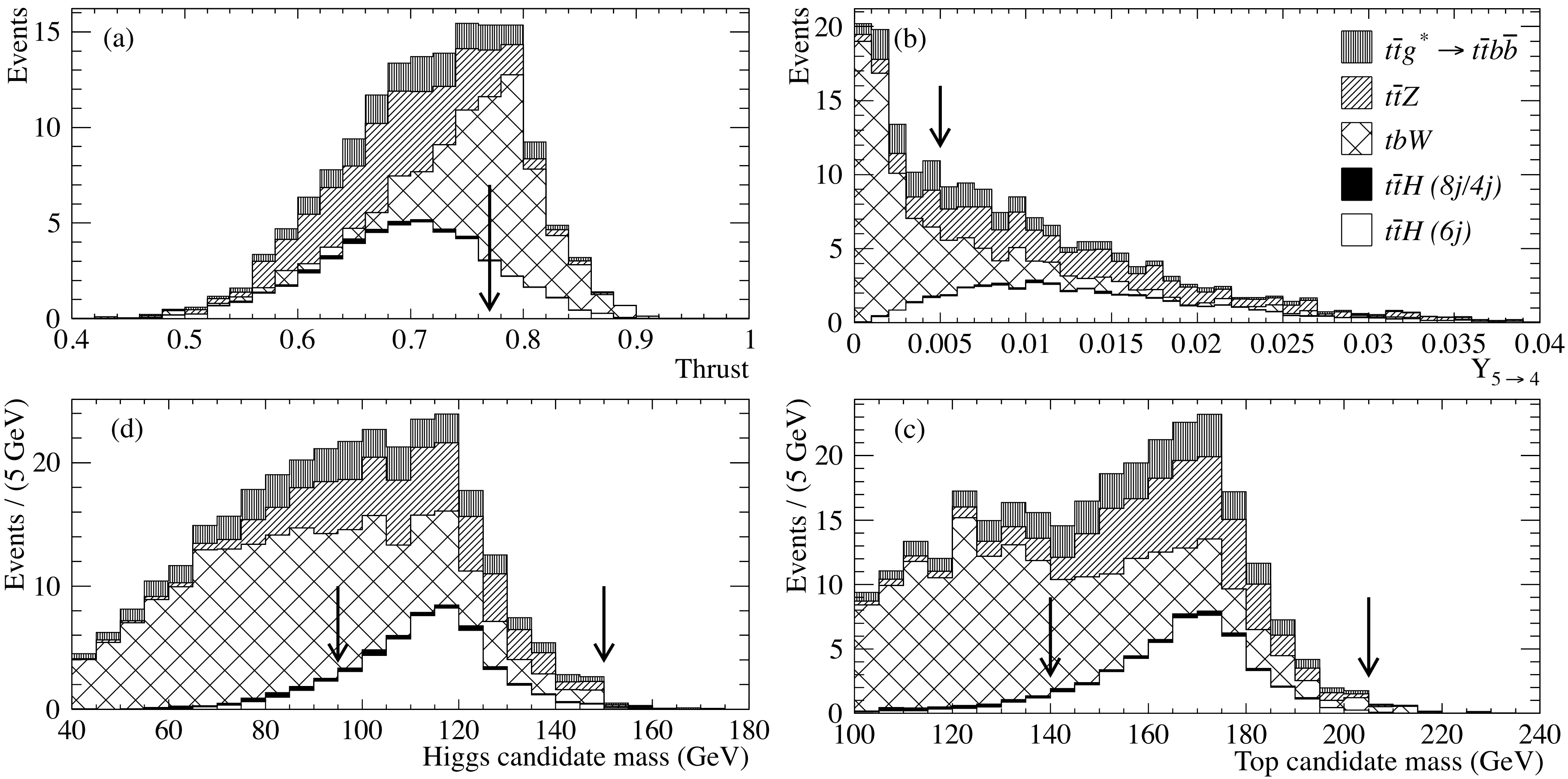
Selection based on:

- Lepton ID based on calorimeter energies
  - reduces fake leptons
- Impact parameter significance
  - reduces contamination from bottom and tau decays
- Jet-based discriminants (**"LAL Lepton Finder"**)
  - good for isolation

Background Reduction

Arrows show cut values.

Fast sim. 1-L + 6-Jet mode
lumi. = 1 ab^{-1}, beam polarization (e^-,e^+) = (-0.8,+0.3)



In each of these 4 plots, all the events selection criteria are applied except for the cut on the variable shown.

Result Summary

R. Yonamine -- 500 GeV

lumi. = 1 ab^{-1}
beam polarization (e^-,e^+) = (-0.8,+0.3)

Cut-based analysis

Fast detector simulation

	1-L+6-Jet	8-Jet	Combined
significance	3.7	3.7	**5.2**
accuracy of g_t	14%	14%	**10%**

Full detector simulation

	1-L+6-Jet	8-Jet	Combined
significance	3.1	3.4	**4.6**
accuracy of g_t	16%	15%	**11%**

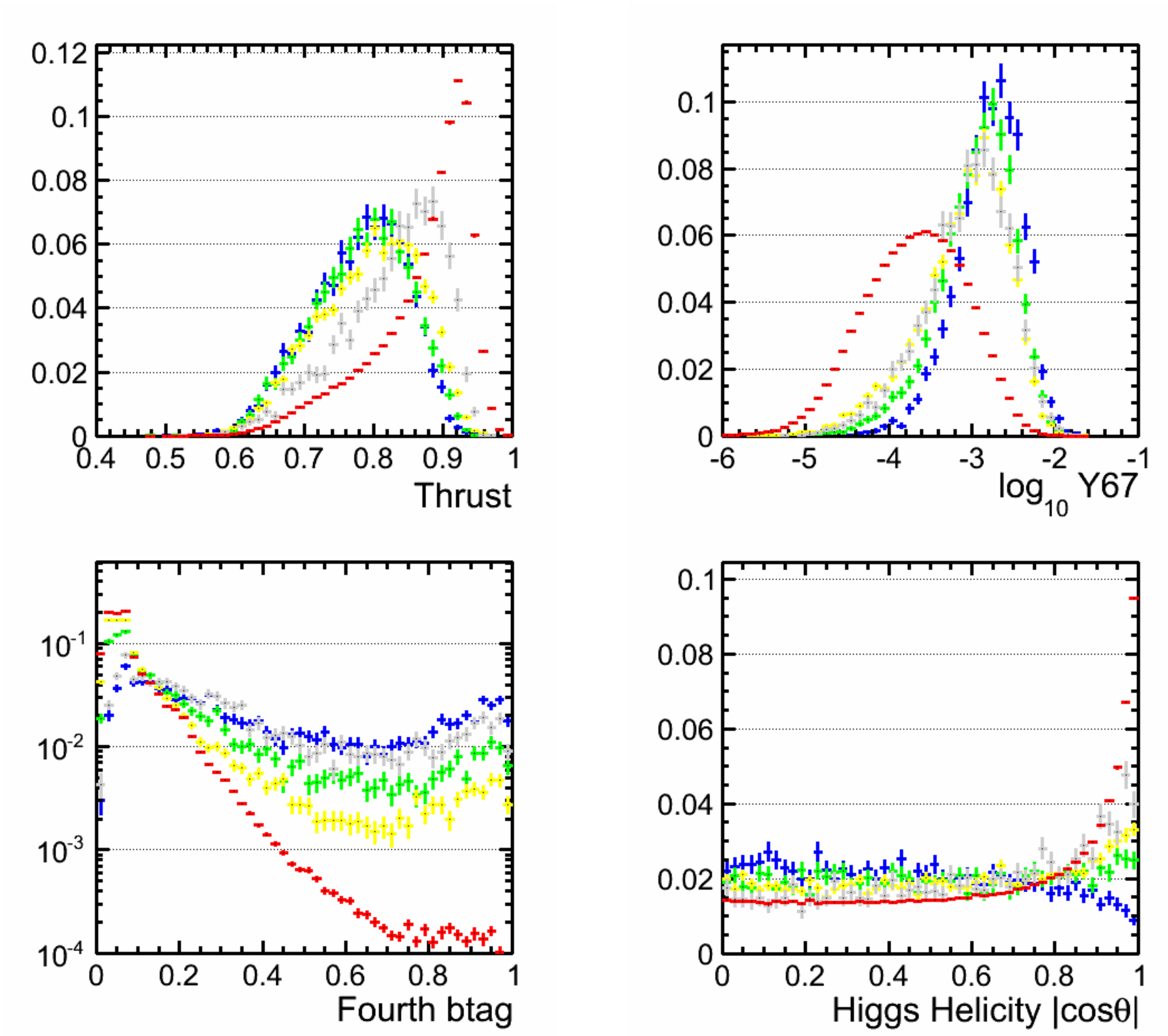
Likelihood analysis (Full detector simulation)

	1-L+6-Jet	8-Jet	Combined
significance	3.2	3.8	**5.0**
accuracy of g_t	16%	13%	**10%**

All results are consistent with each other.

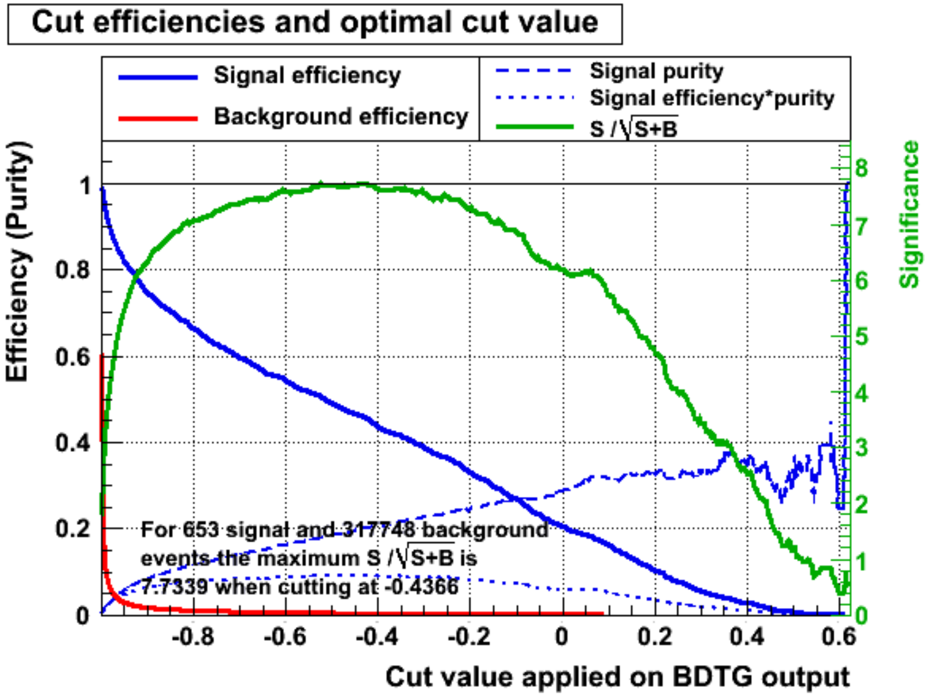
Event Selection

ttH 8 jet
ttH other
ttZ
ttbb
tt



Result Summary (1 TeV)

- Multivariate analysis is used for final results
- Results cross-checked with cut-based analysis



Preliminary results (TMVA):
8 jet mode: **$\Delta y_t/y_t$ = 6.5% (TT)**
6 jet + lepton mode: **$\Delta y_t/y_t$ = 6.2% (T. Price)**
Combined: **$\Delta y_t/y_t$ = 4.5%**
Nicely consistent with SiD results

Summary and prospects

- Progress driven by **DBD** preparation, soon to be finalized.
- We should consider **post-DBD** activities to strengthen the physics case for ILC.
- In particular, we should redo Higgs analyses with Higgs mass of **125 GeV** for $\sqrt{s}$=250, 350, 500 GeV. We have nice simulation tools available prepared for DBD and we should exploit them.
  - The **event generation** can take some time which should ideally start soon.
- We were well-prepared for the Higgs discovery in terms of physics analysis. We should be equally well-prepared for **BSM** results, particularly those that would be discovered at the LHC in the coming few years.
  - Crucial for updating the case for ILC in the **fast-track** construction scenario
- Analysis strategies should be formed to update BSM search strategies (**SUSY** in particular), in light of the latest LHC results. The benchmark scenarios discussed in the DBD should be a good start.